Correlation of Static Stress Changes and Earthquake Occurrence in the North Aegean Region

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Abstract – A systematic analysis is made of static Coulomb stress changes and earthquake occurrence in the area of the North Aegean Sea, Greece, in order to assess the prospect of using static stress changes to construct a regional earthquake likelihood model. The earthquake data set comprises all events of magnitude M ≥ 5.2 which have occurred since 1964. This is compared to the evolving stress field due to constant tectonic loading and perturbations due to coseismic slip associated with major earthquakes (M ≥ 6.4) over the same period. The stress was resolved for sixteen fault orientation classes, covering the observed focal mechanisms of all earthquakes in the region. Analysis using error diagrams shows that earthquake occurrence is better correlated with the constant tectonic loading component of the stress field than with the total stress field changes since 1964, and that little, if any, information on earthquake occurrence is lost if only the maximum of the tectonic loading over the fault orientation classes is considered.

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Moreover, the information on earthquake occurrence is actually increased by taking the maximum of the evolving stress field since 1964, and of its coseismic–slip component, over the fault orientation classes. The maximum, over fault orientation classes, of linear combinations of the tectonic loading and the evolving stress field is insignificantly better correlated with earthquake occurrence than the maximum of the tectonic loading by itself. A composite stress–change variable is constructed from ordering of the maximum tectonic loading component and the maximum coseismic–slip component, in order to optimize the correlation with earthquake occurrence. The results indicate that it would be difficult to construct a time–varying earthquake likelihood model from the evolving stress field that is more informative than a time–invariant model based on the constant tectonic loading.

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Key words: Earthquake prediction, static stress changes, Greece

Introduction

Coseismic stress changes in the vicinity of strong earthquakes suggest that perturbations of 0.1 to 1 bar may affect the occurrence of other earthquakes. Changes in the occurrence rate of local and regional seismicity (TODA and STEIN, 2003; TODA *et al.*, 2005; MALLMAN and ZOBACK, 2007), as well as observed clustering of strong earthquakes (PAPADIMITRIOU and KARAKOSTAS, 2003; PAPADIMITRIOU *et al.*, 2004), suggest that failure on one fault may affect earthquake occurrence on another fault, with changes to the static stress field being an obvious physical mechanism (STEIN *et al.*, 1997). Detailed studies of stress changes and seismicity following the occurrence of major earthquakes provide a body of anecdotal evidence that the location of aftershocks,

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ensuing major events and other changes in seismicity patterns in the vicinity of a major earthquake can often be explained by changes in the static stress field resulting from coseismic slip associated with the major earthquake (e.g., KING *et al*., 1994a; DENG and SYKES, 1997; HARRIS, 1998 and references therein; ROBINSON and MCGINTY, 2000; PAPADIMITRIOU and SYKES, 2001; STACEY *et al*., 2005 and references therein). Coseismic stress changes have been incorporated as an important component in time–dependent probabilistic hazard assessment models (STEIN *et al*., 1997; HARDEBECK, 2004; MICHAEL, 2005; PARSONS, 2005; among others), and poroelasticity effects and post–earthquake relaxation associated with coseismic stress transfer have been introduced to account for the spatiotemporal distribution of aftershocks (COCCO and RICE, 2002; POLLITZ *et al*., 2006; PERFETTINI and AVOUAC, 2007; SAVAGE, 2007).

A previous study, in a wider region of Greece, compared the evolving stress field and precursory scale increase approaches to long–term seismogenesis (PAPADIMITRIOU *et al*., 2006). It was found that recent major earthquakes are largely consistent with both approaches, and also that the evolving stress field was already positive for the occurrence of a major earthquake before the onset of the precursory scale increase, i.e., a long time (years to decades) before the actual time of the earthquake. This is further anecdotal evidence that the evolving stress field can provide an explanation for temporal and spatial fluctuations in seismicity.

Here we attempt to advance these studies beyond the anecdotal stage by systematically comparing the evolving stress field and earthquake occurrences in an extended region over an extended period of time. The goal is to be able to use static stress changes to construct a regional earthquake likelihood model (FIELD, 2007). For the evolving stress field calculations a purely elastic model is used that takes into account both the coseismic slip of the stronger events and the long term tectonic loading on the major regional faults. Moreover, the stress field is calculated each time according to the faulting type of the target fault. This model has proved to be effective in predicting the locations of future earthquakes (e.g. DENG and SYKES, 1997; PAPADIMITRIOU and SYKES, 2001), while in many investigations tectonic loading is not included and assumptions are made about the directions and magnitudes of regional stresses. An intermediate step attempted here is to establish the level of correlation between static Coulomb stress changes and seismicity. The North Aegean Sea region in Greece is selected for this investigation because it has an adequate number of strong (M≥6.4) earthquakes which are included in the stress evolutionary model, whose coseismic slip is considered to perturb the evolving stress field, along with an adequate number of moderate (M≥5.2) events which are inspected for triggering. Our data sample starts at 1964, from which time the location of earthquakes became more accurate, and the determination of focal mechanisms is more reliable for the stronger events and available for many of the smaller magnitude ones.

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Data and methods

The North Aegean study region covers the latitude range 38.3 – 40.5 degrees N. and longitude range 23.5 – 26.5 degrees E. All earthquakes with M ≥ 5.2 in the Aristotle University of Thessaloniki (AUTH) catalogue since 1964 (67 events) are included (see Appendix for a list), and all earthquakes with M ≥ 6.4 (8 events) are considered to contribute to the stress field perturbations. The threshold of 6.4 is chosen because the coseismic slip of such events is sufficiently large to disturb the stress field. In addition, the fault plane solutions of these stronger events have been determined by waveform modeling, and the only other event with M ≥ 6.0 in our catalogue is the one in 1965 with

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M6.1 (see Appendix). The 67 earthquake locations, and available focal mechanisms for 27 events, are shown in Figure 1. For 40 earthquakes the focal mechanism is unknown and must be inferred from that of nearby earthquakes, albeit with some uncertainty.

When searching for a potential correlation between static stress changes and seismicity changes, one approach is to calculate these changes for the nodal planes of the subset of shocks with known focal mechanisms (STEIN, 1999). Since the stress field depends on the fault orientation, it is necessary to calculate the stress field for a representative set of fault orientation classes, which cover all the earthquakes in the catalogue. From a computational perspective, the number of classes should be as small as possible. The distribution of strike angles, dip angles and rake angles in the 27 known focal mechanisms is shown in Figure 2. From these distributions, it was possible to divide the strike angles into 5 groups, the dip angles into 3 groups, and the rake angles into five groups. In this division, the M 6.6 earthquake of 1967 Mar. 4, of oblique normal faulting, formed a group of its own in both strike angle and rake angle. All the known focal mechanisms were found to be contained in only 15 of the 75 resulting possible classes for combinations of strike angle, dip angle and rake angle groups. However, a sixteenth class was included, in which no earthquakes in the current data base fall, to allow for the possibility, however unlikely, of earthquakes occurring with very different focal mechanisms from those observed so far. Table 1 shows how the 15 classes were derived from combinations of ranges of strike angle, rake angle and dip angle. Where earthquakes are observed in a particular class, the restricted range of dip angles actually spanned by the earthquake focal mechanisms in the class is shown in the column corresponding to the broader range used to define the class, and is followed in parentheses by the number of earthquake focal mechanisms observed in the class.

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Figure 3 shows how the so-defined classes were used to infer fault–orientation classes for the other 40 earthquakes in the catalogue. The inference is based on observed spatial clustering of the $M \geq 5.2$ events and the similarity of the known fault plane solutions among neighboring events, although disagreements have been observed in some cases. These disagreements may be partly due to the limited amount of input information for the routine determination of focal mechanisms for the smaller and moderate events. In these cases the more representative faulting type, meaning the one that is more compatible with the orientation of the regional stress, is considered as the dominant faulting pattern. The rectangles in Figure 3 each correspond to a fault orientation class, and earthquakes without well–defined focal mechanisms located in a given rectangle are assumed to belong to the same fault orientation class as the earthquakes with known focal mechanisms in the same rectangle. For each fault orientation class, the faulting type is represented by average values of the strike, rake and dip angles, as given in Table 2. There are only three isolated earthquakes, which cannot be assigned to any fault orientation class. These are linked to locations with no historical or instrumental recordings of strong ($M \geq 6.0$) events and the seismicity is sparse, so that faults cannot easily be identified.

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Stress calculations

The evolving stress field is considered to have two main components – a constantly accumulating component due to tectonic loading on the major faults in the region, and a component consisting entirely of jumps due to coseismic slip accompanying the major earthquakes (DENG and SYKES, 1997). Interseismic stress accumulation between the strong events is modeled by "virtual negative displacements" along major faults in the entire region under study, using the best available information on long–term

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slip rates. These virtual dislocations are imposed on the faults with the sense of slip opposite to the observed slip. The magnitude is incremented according to the long–term slip rate of the fault. This virtual negative slip is equivalent to constant positive slip extending from the bottom of the seismogenic layer to infinite depth. Hence, tectonically induced stress builds up in the vicinity of faults during the time intervals between earthquakes. All computed interseismic stress accumulation is associated with the deformation caused by the time–dependent virtual displacement on major faults extending from the free surface up to the depth at which earthquakes and brittle behavior cease (~15 km).

The major regional faults in our study area, which accommodate strain accumulation culminating in earthquake occurrence, are mainly submarine and therefore field information on their properties is sparse. Recent seismic activity for which hypocentral determinations are available is used to define these fracture lines, and their strike, dip and rake are defined according to the reliable fault solutions of the stronger (M≥6.0) events associated with them (Fig. 4). It is possible to estimate slip rates for these faulting lines directly from the relative motions between GPS stations straddling them. Such information is available from McClusky *et al.* (2000) and Reilinger *et al.* (2006), who interpreted geodetic measurements of crustal motions. The later authors used a simple kinematic block model, including elastic strain accumulations on the block–bounding faults, to quantify relative block motions and to determine present–day rates of the strain accumulation on the block bounding faults. Based on the above, the long–term slip rate for each of the faulting lines is defined approximately, so that their sum is in accordance with the generally accepted motion. We assumed a total of 24 mm/yr of right–lateral slip, placing a large part of this motion (12 mm/yr) on the northern branch and distributing the rest along the four other parallel branches, reducing the amount of slip

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from north to south. For the left–lateral faults a total of 10 mm/yr is assumed. The slip rate values we selected are also in agreement with Armijo *et al.* (2003) who incorporated both the geodetic and geological constraints, providing a description of the present day deformation of the Anatolian–Aegean region. They use in their model localized deformation zones, which are represented by dislocation elements and extended from the base of the lithosphere to the locking depth at the base of the seismogenic layer. The values of slip rates we adopted are equal to 60% of the geodetically determined ones in order to account for the seismically released strain energy. ~~taking into consideration that almost 60% of the geodetic motion is expressed seismically.~~ This choice is based on previous investigations, for example Jackson *et al.* (1994) who concluded that seismicity can account for at most 50% of the deformation in the Aegean area, and King *et al.* (2001) who for the area of the North Anatolian Fault found that the rate of moment release accounts for about 60% of the relative plate motion. Nevertheless, more accurate long–term slip rates for each fault that contributes to the total plate motion will lead to better estimates.

Stress changes associated with both the virtual dislocations and actual earthquake displacements are calculated for an isotropic elastic half space (Erikson, 1986; Okada, 1992) at a depth of 8 km. This depth, the choice of which is not very critical since the faults are almost vertical, was chosen to be several kilometers above the locking depth (15 km) in the evolutionary model. This is the mean of the centroid depths of the stronger events included in our evolutionary model and in agreement with King *et al.* (1994b) who found that seismic slip peaks at mid–depths in the seismogenic layer, and thus deformation must be localized on the faults at these depths. The seismogenic layer in our calculations is taken to extend between 3 and 15 km, based on the centroid depths derived from waveform inversions (6–15 km, mostly) and the focal parameters of accurately relocated aftershocks (e.g. Papazachos *et al.*, 1984; Rocca *et al.*, 1985). The shear modulus and Poisson's ratio are fixed at 33 GPa and 0.25, respectively. The selection of the value of the apparent coefficient of friction, μ', is based on previous results. A value of μ' equal to 0.4 was chosen and considered adequate throughout the calculations, as previous investigations and pertinent tests have revealed (King *et al.*, 1994a; Papadimitriou, 2002).

The annual Coulomb stress change in the absence of fault movement is calculated based on the slip rate, and is resolved for each of the 16 fault orientation classes. This tectonic component of the evolving stress field is illustrated in Figure 5 for ~~six of the orientation classes~~ the faulting types given in Table 2. The stress field was calculated ~~in each case~~ according to the faulting type assigned to each class, and must be viewed in the context of this specific style of fault slip, i.e., strike, dip and rake. This is because stress is a tensorial quantity which changes in space according to the observational plane and sense of slip. As can be seen, the spatial patterns for some of the orientation classes are quite similar, due to relatively small differences between the faulting types that the classes represent. The jumps in the stress field due to coseismic slip accompanying the eight major (M ≥ 6.4) earthquakes since 1964 are illustrated in Figure 6, in which we show the Coulomb stress field change for the actual fault orientation of each earthquake. ~~In each case the Coulomb stress field was resolved for each of the 16 fault orientation classes.~~ Combining these jumps with the tectonic component allowed us to calculate the total change in the Coulomb stress field due to tectonic loading on the major faults and the coseismic slip associated with major earthquakes from the beginning of the catalogue up to just before the occurrence time of any earthquake with M ≥ 5.2. The evolving stress field is then calculated according to the faulting type assigned to the box inside which the earthquake is located.

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All stress field components are calculated on a rectangular grid with 5 km steps. The grid cells are comparable in size to the source area of an earthquake of M 5.4, and larger than that for M 5.2 (WELLS and COPPERSMITH, 1994). However, the contributions to the stress field calculated here have only larger–scale features, so that the values at intermediate points, in particular at the epicenters of M ≥ 5.2 earthquakes, can be well approximated by interpolation from the grid points. Therefore, the grid spacing used here is adequate for the purpose.

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It is the actual stress field that affects earthquake occurrence. The change in the stress field over a period of time is not necessarily a good measure of the actual stress field at the end of the period, unless the stress field was uniform at the beginning of the period. The constant tectonic forcing component has been contributing to the stress field for a long time, and therefore the large scale features of the actual stress field at any time should resemble it in some ways, although the field is modified by every earthquake that occurs, and the effect of earthquakes that occurred prior to the beginning of the catalogue are unknown. The actual stress field at any time cannot be calculated from the available components. But if we were to attempt to construct something that would approximate it, there is no reason to begin the tectonic loading contribution only at the beginning of the catalogue. Equally, there is no reason to begin it at any other time, whether 10 years, 50 years or 500 years prior to the start of the catalogue. In seeking to define a stress variable that is well correlated with earthquake occurrence, we need therefore to consider various combinations of the tectonic loading component and the coseismic slip component of the evolving stress field.

Correlation of stress changes and earthquake occurrence

In what follows, we denote the annual tectonic stress rate by *R*, the coseismic slip component of the evolving stress field by *S*, and the total evolving stress field since the beginning of 1964 by *ESF*. All of these variables are resolved for the 16 fault orientation classes, evaluated on a grid with 5km spacing, and interpolated to intermediate values. *S* and *ESF* can be accumulated from 1964 up to any time of interest, and in particular up to the times of occurrence of M ≥ 5.2 earthquakes.

An error diagram (Molchan, 1990, 1991) is a useful tool for exploring the relation between earthquake occurrence and any scalar variable defined on the domain of possible times and locations of earthquake occurrence. In an error diagram, the *x*–axis represents the proportion of space or space–time in which the scalar variable exceeds some value. The *y*–axis represents the proportion of earthquakes that occur at times and locations when the scalar variable does not exceed the same value. The error diagram is generated from a dense set covering the full range of possible values of the measured variable, with each point in the set contributing a point on the graph. The actual value of the scalar variable is unimportant; the error diagram is the same for any order–preserving transformation of its values (Zechar and Jordan, 2008). If the strategy for declaring an earthquake alarm is that the scalar variable should exceed some value, then the corresponding point on the error diagram shows, on the x–axis, the proportion of space–time occupied by alarms and, on the y–axis, the proportion of unpredicted earthquakes using this strategy. Two points on the error diagram are fixed, irrespective of the variable used: the point (x = 0, y = 1) where there are no alarms and therefore all earthquakes are unpredicted, and the point (x = 1, y = 0) where there are continuous alarms everywhere and therefore no earthquakes are unpredicted. Alarm strategies with no prediction skill are represented by the diagonal joining these two fixed points. If the error diagram lies close to this diagonal, there is little or no correlation between the scalar variable and earthquake occurrence. Skilful strategies are represented by points below the diagonal; if the error diagram lies predominantly below the diagonal, there is a positive correlation between the scalar variable and earthquake occurrence. If the error diagram lies above the diagonal, there is a negative correlation. The area above the error diagram curve has been called the area skill score (ASS) by Zechar and Jordan (2008), and it is used here as a numerical index of the correlation. A value of ASS = ½ corresponds to no correlation between the scalar variable and earthquake occurrence, ASS = 1 to a perfect positive correlation and ASS = 0 to a perfect negative correlation.

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Figure 7a shows the error diagram for the tectonic loading rate R, taking the fault orientation class into account. The proportion of space occupied is estimated from a synthetic earthquake catalogue with earthquakes distributed randomly according to a uniform distribution in time and space, and randomly assigned with equal probability to one of the 15 fault–orientation classes to which past earthquakes belong. The dotted lines shows the 95% tolerance limits for alarm strategies with no skill, so the envelope between these limits is a zone of insignificant deviation from the diagonal (Zechar and Jordan, 2008). The fact that the error diagram for R is outside and below this zone of insignificance shows that R is significantly correlated with earthquake occurrence. This correlation could be used to construct a time–invariant likelihood model for earthquake occurrence in the North Aegean Sea region. Note that R is dependent on the faulting model, which is itself derived in part from past earthquake occurrence. Therefore such a likelihood model would embody the hypothesis that earthquakes are likely to recur on faults where they have occurred in the past, because the faults represent chronic weak zones that re-rupture in preference to the rupture of unfaulted rock.

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Figure 7b is a similarly constructed error diagram for ESF, except that now the stress varies with time as well as location and fault–orientation class. This shows a rather mixed picture and a lower ASS value than Figure 7a. At the high end of the scale, the graph lies below the zone of insignificance showing that *ESF* is correlated with earthquake occurrence, but at the low end of the scale (corresponding to low values of *ESF*), the graph is above the diagonal and touches the upper limit of the zone of insignificance, indicating a weak negative correlation with earthquake occurrence. These contrasting correlations indicate that very high and very low values of *ESF* are both associated with an increased likelihood of earthquake occurrence. The low values of *ESF* are actually quite strongly negative as seen in Figure 8, which shows histograms of *ESF* values for the actual and random catalogues. The negative values at the low end of the distribution of *ESF* (Figure 8a) are responsible for the excursion of the error diagram (Figure 7b) above the diagonal. These negative values are probably due to unknown factors affecting the analysis, such as misclassification of earthquakes into fault–orientation classes or smaller scale changes in the stress field than are accounted for here.

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On the matter of misclassification, several earthquakes could not be placed in a particular class, and actual fault plane solutions are available for less than half of the earthquakes in the catalogue. There is therefore some degree of uncertainty in the majority of the assignments of earthquakes to classes. Also, from a point of view of earthquake hazard, there is usually more interest in knowing the time and location of future earthquakes than the details of their fault orientation. The likelihood of an earthquake occurring at a given location is possibly more closely related to the maximum of the stress field over all classes at that location than to the value in any particular class. Therefore, there is interest in calculating the maximum of the stress field changes over all classes, and examining the associated error diagrams.

Figure 9 is the error diagram for the maximum of R over all 16 fault orientation classes, henceforth denoted max(R), superimposed on a 95% confidence band for the error diagram for R. The fact that the graph lies mostly inside and in some places slightly below the confidence band indicates that R provides no significant information about the fault–orientation of individual earthquakes as classified here. This conclusion is reinforced by a slightly higher value of ASS for max(R) than for R. Hence, in the remainder of our analyses, we consider only the maximum of stress changes over all fault–orientation classes, and address the question of whether we can construct a composite stress variable that is better correlated with earthquake occurrence than max(R). If so, such a variable could potentially be used to construct a time–varying model of earthquake occurrence in the region, which would be more informative than a time–invariant model, constructed from max(R).

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It should be noted that the confidence bands on error diagrams in this paper account for sampling uncertainty only, and not for the uncertainties associated with the modelling of faults, calculations of stress and assignment of earthquakes to fault-orientaion classes. The latter uncertainties are undoubtedly substantial, but no attempt is made here to formally estimate them.

There is no particular time at which the accumulation of stress in the evolving stress field can be assumed to begin. The present stress field is presumably affected by events in the arbitrarily distant past, including slow tectonic changes and sudden coseismic changes. We are unable to include the effects of coseismic changes prior to 1964, but we can include the effect of slow tectonic changes in the arbitrarily distant past, for as long a period as these can reasonably be assumed to be static. Therefore we considered variables constructed from the ESF since 1964 plus an arbitrary number of years of additional tectonic loading.

Figure 10 shows error diagrams for the variables max(ESF), max(ESF + 10R), max(ESF + 30R) and max(ESF + 100R). In the latter three variables an extra 10, 30 and

100 years, respectively, of tectonic loading have been added to *ESF*. Figure 10a, when compared to Figure 7b, shows that max(*ESF*) is better correlated with earthquake occurrence than *ESF* itself, and that the negative correlation seen for low values of *ESF* in Figure 7b is no longer present, since the graph lies significantly below the diagonal for nearly all of its length. However max(*ESF*) is not as well correlated with earthquakes as max(*R*), as can be seen by comparing Figure 10a with Figure 9. The error diagram for max($ESF + 10R$), shown in Figure 10b, is much closer to that of max(*R*), and lies within the 95% confidence band of the latter for much of its length, although it lies partly below the band at the top end, indicating a better correlation with earthquake occurrence than max(*R*) in this range, and above the band for middle–range values. The error diagram for max($ESF + 30R$), shown in Figure 10c, is closer again to that of max(*R*), and lies toward the low end of the confidence band for max(*R*), though not outside of it, for a longer range at the top end. However, a section of the lower end lies above the confidence band. The diagram for max($ESF + 100R$) appears to be the best of all the error diagrams in Figure 10, in that the area skill score is highest, although no higher than that for max(*R*). Moreover, the error diagram lies entirely within the 95% confidence band of that for max(*R*).

Increasing the tectonic loading beyond 100 years tends to shift the error diagram closer to that of max(*R*). It appears therefore that no variable of the form max($ESF + cR$), where c is a positive constant, is better correlated with earthquake occurrence than max(*R*) itself. Therefore, it is necessary to consider other ways of defining composite statistics, which combine the earthquake–related information from the tectonic loading and coseismic–slip components of the evolving stress field. In so doing it is convenient to work with the raw variables *S* and *R*, which are independent, rather than with *ESF*, which is a mixture of the two. The error diagrams for *S* and max(*S*) are shown in Figure 11. The

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graph for S, when compared with the zone of insignificance, shows that S is hardly correlated with earthquake occurrence, as confirmed by the ASS value of 0.47. The graph for max(S) shows a weak but marginally significant correlation with earthquake occurrence, with an ASS value of 0.57.

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Contributing to this result is the fact that many of the smaller events, which can be considered as aftershocks of the main events, are located in stress shadows created by the coseismic slip of the main event. Either the present slip models of the main events are not detailed enough to predict their locations or the assignment of many of the minor events to fault orientation classes is in error.

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Since it is the ordering of values that determines the error diagram, it is of interest to consider whether statistics based only on the ordering of values within components of the stress field may be more closely related to earthquake occurrence than statistics derived from linear combinations of the components. Therefore, as an alternative to the statistics of the form max(ESF + cR) discussed above, consider a composite statistic based on the ordering of values of max(S) and max(R), rather than the actual values. For a given value x of max(S), let s be the proportion of earthquakes in a random catalogue that have a lower value of max(S) than x. Likewise for a given value y of max(R), let r be the proportion of earthquakes in a random catalogue that have a lower value of max(R) than y. Then, if a point in space has values x and y for max(S) and max(R), respectively, we define the composite statistic

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$$Q(c) = s + cr \qquad (1)$$

For c = 0, the area skill score for $Q(c)$ is 0.57 – the same as for max(S). As c is increased, the value of ASS increases until c = 27, then decreases gradually. For c = 100,

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the area skill score is 0.75 – the same as for max(R). Thus, the area skill score for $Q(c)$ is maximized when c = 27, although the maximum value of ASS so attained exceeds that for max(R) by only 0.01. Figure 12 shows the error diagram for Q(27), compared to 95% confidence limits for the error diagram for max(R). Nowhere does the graph lie outside the confidence limits for max(R). However, near the top end it touches the lower limit. Neglecting the lack of statistical significance, we can examine the probability gain that could possibly be achieved from this statistic. Figure 13 shows the relative proportion of earthquakes predicted by Q(27) compared with that predicted by max(R) as a function of the proportion of space–time occupied. This ratio can be interpreted as a probability gain. The maximum gain of 3.5 applies to about 10% of predicted earthquakes using Q(27). Thus the advantage of using Q(27) rather than max(R) can be approximated to a probability gain of 3.5 for 10% of earthquakes and 1 for the remaining 90%. This would give a (geometric) mean probability gain per earthquake of 1.13, rather lower than existing models for long–range and short–range forecasting based only on the times, magnitudes and locations of previous earthquakes (Console et al., 2006). Therefore, there is no indication from these data that changes in static stress could be used to produce a time–varying model of earthquake occurrence that would be significantly more informative than a time–invariant model, or as informative as existing time–varying models.

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Conclusion

The available earthquake, fault and geodetic data have allowed the large scale features of the coseismic–slip contribution to the evolving stress field since 1964 and the constant tectonic loading in the north Aegean Sea region to be evaluated. An analysis using error diagrams has shown that the constant tectonic stress loading and its maximum

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over all orientation classes are each well correlated with the location of M ≥ 5.2 earthquakes in the region since 1964.

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The maximum of the tectonic loading could be used to construct a static model of earthquake occurrence. The total evolving stress field since 1964 is less well correlated with earthquake occurrence than the tectonic loading. This agrees with Kagan et al. (2005) who found that the most robust relationship is between the tectonic loading and the locations and mechanisms of earthquakes in southern California during 1850–2004, while the inclusion of the cumulative coseismic effects from past earthquakes did not significantly improve the correlation. Taking the maximum of the evolving stress field and that of its coseismic component over all fault orientation classes improves the correlation of these variables with earthquake occurrence. The maximum, over fault orientation classes, of linear combinations of the tectonic loading and the evolving stress field is insignificantly better correlated with earthquake occurrence than the maximum of the tectonic loading by itself. Contributing to this result is the fact that many aftershocks are located in apparent stress shadows created by the coseismic slip of the main events. This is consistent with Parsons (2002), who found that only 61% of aftershocks could be associated with stress enhancements. It suggests that the actual stress changes resulting from the main events are more complex than those predicted by the present slip models and the assignment of many of the minor events to fault orientation classes may be in error.

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However, the coseismic component of *ESF* contains some information on the locations and times of occurrence of the larger earthquakes independent from the tectonic loading. An example has been given of a composite statistic constructed from the maximum of the tectonic loading and that of the coseismic–slip component of *ESF* that is slightly better correlated with earthquake occurrence than the maximum of the tectonic loading by itself. Such statistics may be useful in building time–varying earthquake likelihood models. However, with the current data, the probability gain over static models is likely to be quite small. When a larger data set becomes available, including focal mechanisms for more of the smaller earthquakes and covering a longer time–period, the coseismic–slip component of the evolving stress field is likely to provide more information toward prediction of time–varying earthquake occurrence.

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Appendix

Catalogue of earthquakes origin times, locations, magnitudes, fault orientation classes and fault plane solutions (where available).

Date	Time	Lat.	Long.	Depth	M	Class	Strike	Dip	Rake	Ref
1964 Feb. 23	22:41	39.2	23.7	10	5.4	7				
1964 Apr. 11	16:00	40.3	24.8	33	5.5	3	220	89	179	1
1964 Apr. 29	04:21	39.2	23.7	20	5.6	7				
1964 Apr. 29	17:00	39.1	23.5	15	5.2	7				
1965 Mar. 9	17:57	39.16	23.89	7.0	6.1	8	44	75	175	2
1965 Mar. 9	17:59	39.3	23.8	0.1	5.7	8				
1965 Mar. 9	18:37	39.3	23.9	33	5.2	8				
1965 Mar. 9	19:46	39.1	23.9	19	5.2	8				
1965 Mar. 13	04:08	39.1	24	11	5.3	8				
1965 Mar. 13	04:09	39	23.7	33	5.5	7				
1965 Aug. 23	14:08	40.5	26.2	33	5.6	1				
1965 Dec. 20	00:08	40.2	24.8	33	5.6	3	132	32	-90	1
1967 Mar. 4	17:58	39.2	24.6	10	6.6	10	313	43	-56	2
1968 Feb. 19	22:45	39.5	25	15	7.1	5	216	81	173	3
1968 Feb. 20	02:21	39.6	25.4	8.0	5.2	6				
1968 Mar. 10	07:10	39.1	24.2	0.1	5.5	9				
1968 Apr. 24	08:18	39.3	24.9	20	5.5	5				
1969 Apr. 6	03:49	38.5	26.4	16	5.9	15				
1975 Mar. 17	05:11	40.36	26.02	15	5.3	1				
1975 Mar. 17	05:17	40.39	26.06	15	5.4	1				
1975 Mar. 17	05:35	40.38	26.1	16	5.8	1				
1975 Mar. 27	05:15	40.4	26.1	15	6.6	1	68	55	-145	2
1975 Mar. 29	02:06	40.42	26.03	33	5.7	1				
1979 June 14	11:44	38.74	26.5	8	5.9	15	262	41	-108	2
1980 Nov. 12	16:04	39.1	24.3	0	5.3	9				
1981 Dec. 19	14:10	39	25.26	10	7.2	11	47	77	-167	3
1981 Dec. 21	14:13	39.17	25.43	10.5	5.2	11				
1981 Dec. 27	17:39	38.81	24.94	6	6.5	11	216	79	175	2
1981 Dec. 29	08:00	38.7	24.84	15	5.4	11	235	81	153	4
1982 Apr. 10	04:50	39.94	24.61	17.4	5.2	3				
1982 Jan. 18	19:27	39.78	24.5	7.0	7.0	4	233	62	-177	2
1982 Jan. 18	19:31	39.44	24.61	35	5.6	10				
1983 Aug. 6	15:43	40	24.7	9	6.8	3	50	76	177	3
1983 Oct. 10	10:17	40.23	25.32	11	5.4	2	70	64	176	5
1984 May 6	09:12	38.77	25.64	9	5.4	13	237	89	-161	5
1984 July 29	01:58	40.37	25.97	15.9	5.2	1				
1984 Oct. 5	20:58	39.1	25.3	22.6	5.6	11				
1986 Mar. 25	01:41	38.34	25.19	15	5.5	12	163	59	-22	5
1986 Mar. 29	18:36	38.37	25.17	14	5.8	12	149	63	15	5

Date	Time	Lat.	Long.	Depth	M	Class	Strike	Dip	Rake	Ref
1986 Apr. 3	23:32	38.35	25.1	1	5.2	12				
1986 June 3	06:16	38.31	25.1	6.7	5.3	12				
1986 June 17	17:54	38.32	25.11	31.8	5.4	12				
1987 Aug. 6	06:21	39.19	26.27	13.4	5.2	U				
1987 Aug. 8	22:15	40.09	24.89	11.1	5.3	3				
1987 Aug. 27	16:46	38.91	23.78	6.3	5.2	7				
1988 May 30	16:47	40.25	25.85	2.8	5.2	1				
1989 Mar. 19	05:36	39.23	23.57	15	5.4	7	320	90	0	4
1989 Sep. 5	06:52	40.15	25.09	15	5.4	2	64	34	-159	4
1992 July 23	20:12	39.81	24.4	8	5.4	4	272	51	-148	5
1994 May 24	02:05	38.82	26.49	21.4	5.5	15	258	54	-135	4
1997 July 16	13:06	39.04	25.22	15	5.2	11				
1997 Nov. 14	21:38	38.72	25.91	10	5.8	13	58	83	175	5
1998 Apr. 11	09:29	39.9	23.88	7	5.2	U				
2000 Aug. 22	03:35	39.59	23.85	11	5.2	U				
2001 June 10	13:11	38.6	25.57	33.6	5.6	14	151	74	-12	4
2001 July 26	00:21	39.06	24.25	15	6.4	9	148	76	-1	4
2001 July 26	00:34	39.05	24.27	13.9	5.3	9				
2001 July 26	02:06	38.96	24.34	14.6	5.2	9				
2001 July 26	02:09	38.9	24.37	9.8	5.3	9				
2001 July 30	15:24	39.14	24.13	15	5.4	9	259	58	-72	4
2001 Oct. 29	20:21	39.09	24.28	10	5.4	9				
2003 July 6	19:10	40.37	26.25	20	5.5	1				
2003 July 6	20:10	40.42	26.13	17	5.2	1				
2004 June 15	12:02	40.37	25.81	12	5.2	1	251	85	168	4
2004 Nov. 22	19:13	38.45	25.68	20	5.2	14				
2005 Aug. 24	03:06	39.68	25.56	29	5.2	6	244	68	-156	4
2006 Dec.21	18:30	39.32	23.6	23	5.3	7	144	76	-15	4

U: Orientation class unknown

Ref.: 1: McKenzie (1972); 2. Taymaz et al. (1991); 3. Kiratzi et al. (1991); 4. Harvard CMT solutions; 5. Louvari (2000).

Tables

Table 1. Fault orientation classes and number of earthquakes in each (in parentheses)

Strike angle range	Rake angle range	Dip angle range		
		30° – 45°	50° – 70°	70° – 90°
45° – 70°	-177° – -135°	34° (1)	55° (1)	77° (1)
45° – 70°	-116°	37° (1)		
45° – 70°	175° – 177°		64° (1)	75° – 83° (3)
130° – 165°	-22 – 15°		59° – 63° (2)	74° – 76° (3)
215° – 240°	-167° – -161°		62° (1)	89° (1)
215° – 240°	153° – 179°			79° – 89° (4)
250° – 275°	-156° – -108°	41° (1)	51° – 68° (3)	
250° – 275°	168°			85° (1)
313°	-56°	43° (1)		

Table 2. Representative strike, dip and rake angles for fault orientation classes

Class number	Strike angle	Dip angle	Rake angle
1	65	55	-145
2	65	55	-165
3	50	76	177
4	233	62	-177
5	216	81	173
6	244	68	156
7	144	76	-15
8	44	75	175
9	148	76	-1
10	313	43	-56
11	47	77	-167
12	156	60	-5
13	60	85	-170
14	151	74	-12
15	260	50	-120
16	80	25	90

Captions for figures

Fig. 1. Map of the North Aegean study region, showing locations of 67 earthquakes with $M \geq 5.2$ since 1964 and focal mechanisms where available.

Fig. 2. Histograms of (a) strike angle, (b) dip angle, and (c) rake angle, for earthquakes with determined fault plane solutions in the study region.

Fig. 3. Map of the study region showing rectangles for grouping earthquakes into fault orientation classes.

Fig. 4. Map of the study area showing major earthquake focal mechanisms and associated faults, and major fracture lines on which the tectonic loading is assumed to accumulate.

Fig. 5. Annual Coulomb stress changes associated with the tectonic loading on the major regional faults. The stress pattern is calculated for each one of the 16 different faulting types (See table 2). The color scale in the bottom gives the changes in stress in bars. ~~Tectonic loading component of evolving stress field (red: positive, green: neutral, blue: negative) mapped for fault orientation classes 1 – 6 (See Table 2).~~

Fig. 6. Coulomb stress changes ~~(red: positive, green: neutral, blue: negative)~~ associated with the coseismic slips of for the eight major ($M \geq 6.4$) earthquakes that occurred in the study area since 1964. The stress field is calculated according to the faulting type of the modeled event. The color scale in the bottom gives the changes in stress in bars. (a) 1967 Mar. 4, M6.3, Strike:313, Dip:43, Rake:-56; (b) 1968 Feb. 19, M7.1, Strike:216, Dip:81, Rake:173; (c) 1975 Mar. 29, M6.6, Strike:68, Dip:55, Rake:-145; (d) 1981 Dec. 19, M7.2, Strike:47, Dip:77, Rake:-167; (e) 1981 Dec. 27, M6.5, Strike:216, Dip:79, Rake:175; (f) 1982 Jan.18, M7.0,

Strike:233, Dip:62, Rake:-177; (g) 1983 Aug.6, M6.6, Strike:50, Dip:76, Rake:175; (h) 2001 July 26, M6.4, Strike:148, Dip:76, Rake:-1.

Fig. 7. Error diagram for (a) annual tectonic Coulomb stress rate *R* and (b) evolving Coulomb stress field since 1964 (*ESF*) resolved into 15 fault orientation classes. For the purposes of computing the proportion of space–time occupied, all classes were given equal weighting. The dotted lines are 95% tolerance limits for alarm strategies with no skill. The area skill score (ASS) is also given.

Fig. 8. Histograms of (a) *ESF* values (bars) corresponding to the times of occurrence, location and fault orientation class of earthquakes in the catalogue. (b) *ESF* values corresponding to randomly chosen times, locations and 15 fault orientation classes.

Fig. 9. Error diagram for max(R), the maximum, over all 16 fault orientation classes, of the annual tectonic loading (R), and 95% confidence band of error diagram for R. The similarity of this diagram to that for R itself indicates that R contains little information on the fault orientation class of earthquakes.

Fig. 10. Error diagram for (a) max(ESF), (b) max(ESF + 10R), (c) max(ESF + 30R), and (d) max(ESF + 100R). In (b–d), the 95% confidence band of the error diagram for max(R) is also shown.

Fig. 11. Error diagram for S, the coseismic contributions to the evolving stress field, and max(S), its maximum over the 16 fault orientation classes.

Fig. 12. Error diagram for the composite statistic Q(27) (see text) compared to 95% confidence band for error diagram of max(R).

Fig. 13. Proportion of earthquakes predicted by $Q(27)$ relative to that predicted by $\max(R)$ as a function of the proportion of space–time occupied.

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